Design and Development of the Heat Redistribution System for the Europa Clipper Spacecraft

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This paper details the conceptual design of the Heat Redistribution System (HRS) used for thermal control of the Europa Clipper spacecraft. The solar powered spacecraft will launch in the early 2020s and will study Jupiter's Icy moon, Europa, where previous investigations have indicated the possibility of a liquid water ocean underneath its ice-encrusted surface. The spacecraft will execute multiple flybys of Europa while relying on the HRS for thermal control of the spacecraft bus. The HRS utilizes a Mechanically Pumped Fluid Loop (MPFL) to reclaim waste heat from an avionics and payload electronics compartment and redistribute it to other parts of the spacecraft, such as the propulsion module structure and the louver-radiator assembly. A "replacement heater block" provides supplemental heat when needed to maintain the spacecraft hardware above its allowable flight temperatures. Additionally, a set of thermal control valves autonomously actuate to reduce the fluid flow through the radiator during cold environment cases. The HRS was used in previous flight projects at JPL such as Mars Science Laboratory, but the uniqueness of the Europa Clipper mission has mandated changes to previous HRS designs; the most significant design drivers and design changes for this iteration of the HRS are discussed.

Nomenclature

AFT	=	Allowable Flight Temperature
APL	=	Applied Physics Laboratory
AU	=	Astronomical Unit
CAD	=	Computer Aided Design
CBE	=	Current Best Estimate
CFC-11	=	Tricholorofluoromethane (Freon)
HGA	=	High Gain Antenna
IMU	=	Inertial Measurement Unit
HRS	=	Heat Redistribution System
IPA	=	Integrated Pump Assembly
JPL	=	Jet Propulsion Laboratory

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M2020	=	Mars 2020 mission
MEV	=	Maximum Expected Value
MLI	=	Multi-layer Insulation
MSL	=	Mars Science Laboratory
MV	=	Mixing Valve
REM	=	Rocket Engine Module
RHB	=	Replacement Heater Block
RF	=	Radio Frequency
SA	=	Solar Array
SRU	=	Stellar Reference Unit
TV	=	Throttle Valve
TWTA	=	Traveling Wave Tube and Amplifier

I. Introduction

The Europa Clipper Mission is a NASA project currently in Phase B of its lifecycle. The project is a collaboration between NASA's Jet Propulsion Laboratory (Caltech/JPL) and the John Hopkins University Applied Physics Laboratory (JHU-APL). The mission will characterize the ice shell, subsurface ocean, surface topography, and magnetic environment of the Galilean icy moon Europa using nine different science instruments. Since Europa is located in one of the harshest radiation environments of the Jovian system, previous Europa mission concepts have had a difficult time tackling the implications of this radiation environment on the hardware lifetime and science return capability. To address this the Europa Clipper spacecraft employs a unique trajectory: a long looping orbit around Jupiter with multiple science flybys of Europa, during which the instrument suite will be collecting data. Once in a lower radiation environment outside of the flyby the spacecraft recharges the 350A-hr batteries with the use of the 90 m^2 solar arrays while relaying scientific and engineering data back to Earth. Additionally, the spacecraft baseline design includes a radiation protection mechanical architecture similar to the one employed by the Juno spacecraft: a radiation vault houses the majority of the radiation sensitive spacecraft and instrument electronics with its 10 mm thick aluminum walls.

As an outer planet solar array powered spacecraft, (Figure 1), one of the mission's key and scarcest resources is power. During development of the project concept, several thermal control architecture trade studies were conducted to determine an optimal and appropriate thermal control scheme for the mission. The findings of such trades concluded that an active thermal architecture provides a substantial benefit in power resources over a passive thermal control architecture (Ref. 1). Additionally, an active thermal control architecture provides more robustness to mechanical configuration changes, flight system operations changes, and system power growth (or reduction).

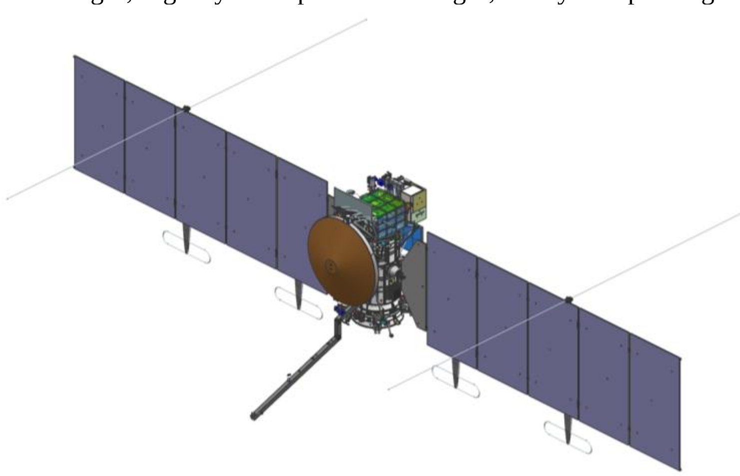

Figure 1: Isometric view of the Europa Clipper Spacecraft

JPL has employed mechanically pumped fluid loop systems in other interplanetary missions, specifically in the Mars exploration program: Pathfinder, MER, MSL, and Mars 2020. (Ref. 2,3,4). However, these missions have had different requirements and constraints that each HRS system must meet and design to. Table 1 shows a summary of the high-level design considerations for each of these referenced missions.

Table 1: Comparison of driving considerations for several missions with an HRS thermal control architecture

	Pathfinder/MER	**MSL/Mars 2020**	**Europa Clipper**
Min AU	0.9AU	0.9AU	0.65AU
Max AU	1.66 AU	1.66 AU	5.6 AU
Energy Source	Solar	Solar & RTG	Solar
Temperature Range	-40˚C to +55˚C	-40˚C to +50˚C	0˚C to +35˚C
HRS used in	Cruise Stage	Cruise Stage + Lander	Spacecraft

The uniqueness of each of the previous missions ultimately led to distinct HRS designs and similarly, Europa Clipper's uniqueness will lead to a new adaptation of the HRS. This paper covers the details of the Europa Clipper and the HRS thermal design for this spacecraft including general architecture, improvements to the fluid-to-interface conductance, routing considerations, the concept of the replacement heater block, addition of the throttle valve and louver, and higher flow rate considerations. It must be noted that during the initial concept phase of the project two noticeably unanswered question were identified: the compatibility of the HRS fluid and hardware to Europa's harsh radiation environment and the extended life of the pump due to long cruise duration to Jupiter. The efforts and study focused on these inquiries have led to findings that can be found in (Ref. 5).

II. Mission Concept Spacecraft Configuration and Thermal Considerations

A. Mission Design

Slated to launch in the early 2020s, the spacecraft must accommodate an interplanetary trajectory with a set of Venus and Earth gravity assists on its way to Jupiter. This trajectory will take the spacecraft as close as 0.65 AU from the sun before continuing on to a maximum distance of 5.6 AU (Figure 2). The spacecraft will orbit Jupiter in a high-eccentricity elliptical orbit with 40-50 flybys of Europa and a few flybys of other Galilean moons. During the majority of its time around Jupiter orbit, most of the instruments will be in low power standby or completely off. The main instrument operation periods will occur approximately two days before each closest approach of Europa and approximately two days after. These flyby periods have the most power and energy stressing modes of the flight system and require battery power to supplement the solar array power generation (Figure 3). The mission design team is optimizing the trajectory geometry such that each instrument is able to obtain significant science with the limited number of flybys. Because each flyby observes different strips of the surface at varying angles, sun orientations, and altitudes, each flyby observation and instrumentation use is unique.

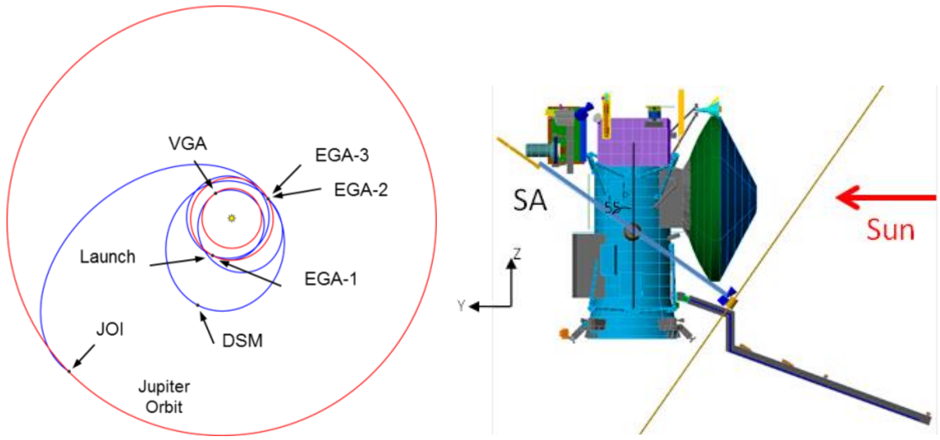

Figure 2: Left: Baseline interplanetary trajectory for the Europa Clipper spacecraft. Right: Thermal Desktop ® model of the nominal spacecraft orientation at <2AU distances from the sun.

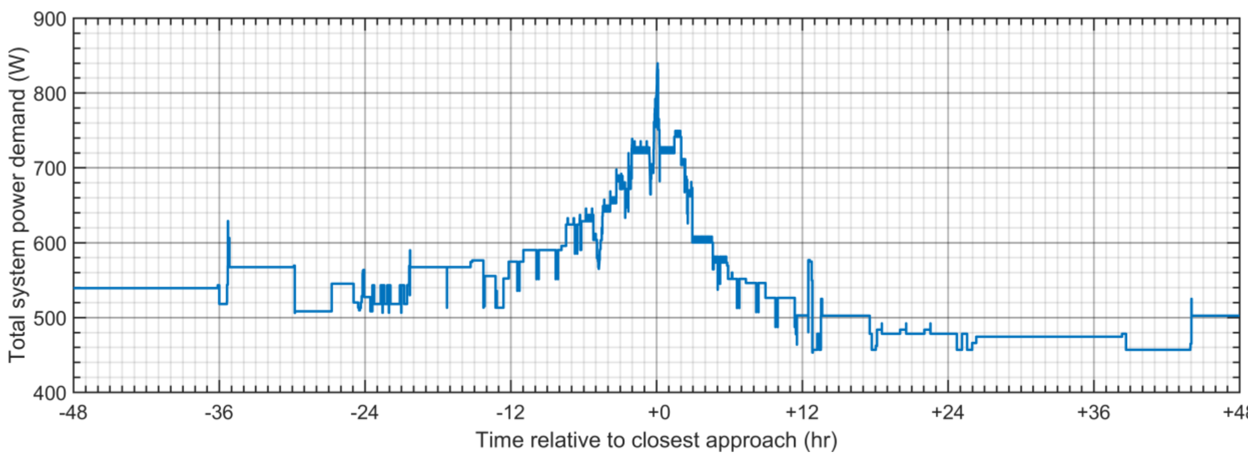

Figure 3: Total system flyby power demand (MEV) starting two days before closest approach and two days after closest approach. Peak power demand occurs at closest approach, although the magnitude and power profile is dependent on the planned science observation for each flyby.

This mission design imposes several considerations for appropriate spacecraft thermal control. The inner cruise phase of the mission imposes a significant environmental load on the spacecraft; the sunlit surfaces of the Multilayer Insulation, (MLI), and exposed spacecraft surfaces are elevated in temperature which not only hampers the ability for the spacecraft to radiate heat out to space but also act as a heat load onto the rest of the spacecraft system. As a result, the spacecraft radiator is sized to accommodate the internal heat dissipation in addition to a solar load 2.3 times that of an earth orbiting spacecraft. The radiator needs to be accommodated in a shaded region of the spacecraft and stringent sun pointing constraints must be placed on the flight system during inner-cruise. The inner cruise portion of the mission is also driving the hot extreme temperatures of the solar array. Nominally, the gimbaled solar arrays can be off-pointed from the sun to maintain them below a predetermined allowable flight temperature, AFT, of 100˚C. However, the solar arrays can be exposed to much more extreme temperatures during loss of attitude control faults. Because of the quick thermal response time of the solar arrays however, a fast responding fault protection scheme must be developed to ensure that the solar arrays are not elevated above their test temperatures.

At Jupiter, the solar load is less than a tenth of a percent what it is at Earth orbit so any radiating surface area becomes a heat leak and drives the heater power demand required to maintain hardware above the AFTs. However, during this mission phase spacecraft power is severely limited due to the capability of the solar arrays at such large distances from the sun. Power is also contested with engineering hardware and payload hardware during the science flybys and telecom passes.

B. Spacecraft Configuration

The spacecraft is composed of three modules: the Radio Frequency, (RF), module, the Avionics module, and the Propulsion module (Figure 4). The avionics module is composed of a vault structure and a nadir-pointed instrument deck. The majority of the spacecraft and payload electronics are located inside the vault; the thick aluminum vault walls aid as protecting the sensitive electronics from Jupiter's radiation environment. The instrument sensors mount on the Nadir Deck, which is located off the vault structure. Three Lithium Ion batteries are also mounted on the external side of the vault. The Propulsion module makes up the majority of the spacecraft by volume and surface area. All of the propulsion subsystem hardware and electronics are housed in this module, along with the thermal radiator, the solar arrays, the magnetometer, and the ice penetrating radar. The fuel and oxidizer tanks are located inside the large cylindrical structure, while their respective pressurant tanks are mounted external to the structure. There are four rocket engine modules (REMs), each with four axial thrust engines and two roll engines. Finally, the RF module is distributed across the vault and propulsion modules; the three-meter diameter high-gain antenna is mounted to the side of the propulsion module, while the TWTAs and radios are located outside and inside the vault respectively.

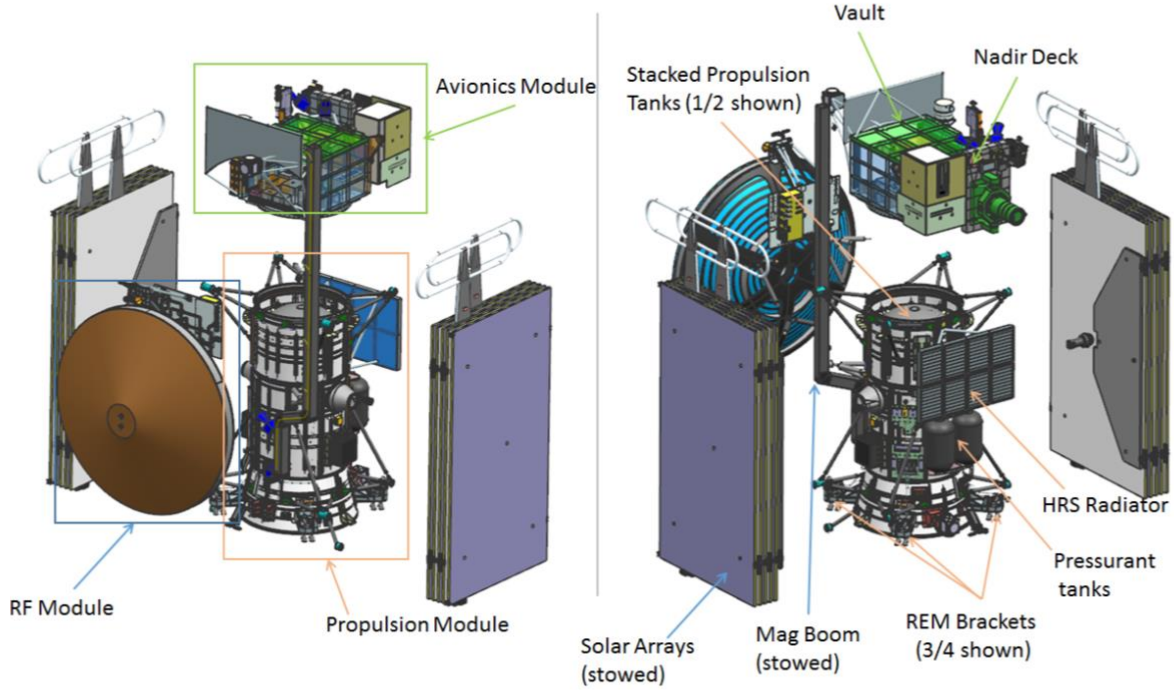

Figure 4: Breakdown of the baseline spacecraft configuration by module (left). Key spacecraft hardware assemblies (right).

The majority of the flight system's hardware dissipation occurs in the avionics and RF module within the vault. However once at Jupiter, most of the spacecraft heater power demand is needed to warm the propulsion module due to its large surface area and also in part because the baselined REMs employ a valve with a moderate conduction path to the rest of the engine nozzle, causing all 24 nozzles to act as radiators in Jupiter. The magnetometer boom, SA and boom launch restraints, and launch vehicle interfaces also add to the heat leaks in this module. Additionally, the freezing point of the bi-prop system places a min AFT of no less than 0 ˚C on all of the propulsion hardware. Due to the physical separation of the vault and propulsion module, the waste heat generated by the electronics at the vault cannot be efficiently spread by conduction alone to maintain the temperature of propulsion module. The thermal coupling between the two modules must be enhanced, and in this case, an MPFL is best suited to harvest waste heat from the electronics vault and transfer it to the propulsion module.

III. HRS Design

A. Overview

To maintain technology heritage, the Europa spacecraft employs a single-phase mechanically pumped fluid loop system very similar to those used in previous JPL flagship flight projects. Figure 5 shows a simplified diagram of the Europa HRS system with key components and driving temperature requirements. The Europa HRS is the main thermal control method used to maintain the vault electronics and propulsion subsystem hardware within their respective allowable flight temperatures, (AFTs). This HRS aids in rejecting excess heat from the vault and spacecraft and transferring this waste heat to the propulsion module. In doing so, the HRS system reduces the electrical heater power demand of the spacecraft.

Figure 5: Simplified Europa HRS diagram and description of key elements

Trichlorofluoromethane or CFC-11 acts as the working fluid; the fluid flows at a rate of 0.75 lpm through 9.5 mm diameter pipes. Waste heat is harvested at the vault and distributed throughout the propulsion module. Three components manage the heat and temperatures of the system: the Replacement Heater Block (RHB), the Mixing Valve/Throttle Valve (MV/TV), and the radiator/louver. The MV and TV are located inside the Integrated Pump Assembly, (IPA), which is also composed of the pump, pump electronics, filters, and accumulator of the HRS. The RHB provides supplemental heat to the system when the flight system hardware generates insufficient waste heat. As waste heat dissipation increases, the RHB power reduces to maintain a minimum heat load into the system. For flight system modes with high power dissipation, excess heat can be rejected via the radiator; as the MV/TV temperature increases, the oil-actuated valves allow additional fluid flow to the radiator. Similarly, as the radiator temperature increases, the louvers open up allowing additional heat rejection to space.

B. HRS Tubing Configuration

Early in the design of the Europa HRS system, the total length of fluid loop tubing required to service the vault and propulsion module was found to be in excess of what previous missions have used. In particular, to keep the components below their maximum AFT limits on the vault, it required an amount of tubing routed on the avionics module that accounted for nearly all the available pressure head in the baseline pump, limiting the available head for the HRS routed on the propulsion structure and radiator.

Once the system pressures exceeded the available head of our baseline, pump, the flow rate fell below the target flow rate, which reduced the thermal conductance between the fluid and hardware. This reduced conductance in turn, led to elevated hardware temperatures, thereby necessitating additional tubing to compensate. Without remediation, the design effort would have continued in a negative feedback loop. To exit this loop, the tubing and interface configurations were reassessed.

A trade with several options was conducted; each configuration had different mass, interface conductance, and implementation impacts (Figure 6). The internally finned tubing was the baseline tube configuration for the vault. This configuration situated the tubes in saddles attached to the structure with caps and fasteners. This was heritage retained from the MSL Rover. Internal finned tubing contributes significant pressure drop, but helps with tube conductance between the fluid and the component interfaces (option 2 in Figure 6). However during the trade, the 3/8” OD, unfinned, flanged, tubing configuration came out as the leading contender due to the reduced pressure drop, simplified implementation, tubing installation process, and mass reduction. The heritage MSL saddled and capped tubing configuration required bonding the tube to both the saddle and the cap and both interfaces were difficult to control the epoxy thickness (colored orange in the tube cross-sections shown Figure 6), which was the primary source of resistance in the conduction path. The flanged configuration only required one bonding interface: right at the thermally controlled interface. The flat surface of the flange allows easier control in minimizing the bond-line thickness, which is key in reducing interface conductance uncertainty. This unfinned, flanged, tubing configuration was chosen for the Avionics, RF, and Propulsion module. Figure 7 shows the significant routing simplification implemented at the vault base panel due to new unfinned flanged tube and bonding configuration.

Figure 6: Four out of several tube cross-section and bonding configuration options that were traded to improve system pressure drop. Note values in the above table are calculated and not measured. Measurements will be made on final geometry selection to confirm theory.

Figure 7: Vault Baseplate Routing comparison of Left: Finned Cap and Saddled Tubing vs. Right: Unfinned, Flanged Tubing.

C. Throttle Valve and Louver

Earlier in the design of the Europa HRS, a single throttle valve was employed to modulate fluid flow to the radiator. Due to manufacturing tolerances, the valve does not fully close; previous missions have had to accommodate a trickle flow of approximately 4% of the full flow. Although this is a small percent of flow, the heat loss through an exposed radiator is still substantial due to the modest size of the radiator (~1.1 m^2 in active radiating area) and the warm fluid inlet temperature of 0℃: approximately 50W were radiated out to space even when radiator was shut. This was a massive tax on the flight system with 13% of the system heat loss during the cold case being due to this trickle radiator flow. Hence an additional valve, (the throttle valve), is used in series to reduce the radiator trickle flow to less than 1%. The CFC-11 however must be maintained above -95℃ to stay well above its freeze point of -111℃; hence, electrical heaters are located at the radiator. In order to keep radiator heater power demand low, louvers are used to further cut the heat loss form the radiator surface to space. Note that the heater power demand for these heaters are far lower than the 63W of heat loss that originally had to be compensated by the electronics waste heat and RHB (Figure 8). The use of both flow reduction and louvers to minimize heater power is a unique feature of the Europa thermal control system, specifically when compared to other HRS designs implemented by JPL.

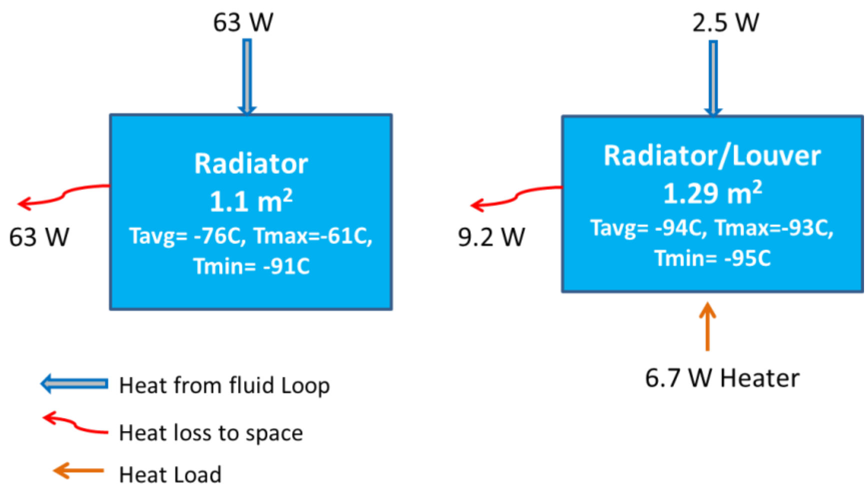

Figure 8: Comparison of the heat loss through the radiator with (left) a single mixing valve and no louvers vs. (right) two valves and louvers.

D. HRS Set Point and Control Scheme

The set points of the RHB, MV/TV, and louvers must be defined appropriately to manage the temperature of the spacecraft hardware. Several considerations are taken into account to determine these set points: temperature requirements of the hardware, the amount of heat transfer from the fluid, and the hardware capability of the RHB, MV/TV, and louvers.

The WCH scenario determines the heat required to be rejected from the spacecraft in order to maintain the hardware below their maximum AFTs. Similarly, the WCC scenario will determine how much heat needs to be supplied to the spacecraft to maintain hardware above their minimum AFTs. Based on this, the expected temperature deltas of the fluid can be determined. Additionally, the maximum AFT of the propulsion module limits the maximum fluid temperature at the inlet of the propulsion module. Hence, even though the vault hardware maximum AFTs are generally 50 ˚C, the fluid temperature delta across the vault must not result in the fluid exiting the vault above 35 ˚C. Additionally, there is noticeable solar heating that occurs at the propulsion module during inner cruise – specifically at the engines and engine brackets– such that the temperature increases across the propulsion module during this case. This imposes an even tighter restriction on the maximum fluid temperature at the inlet of the propulsion module.

In addition to these temperature constraints, it would be counter-productive for the RHB to be on when the valves and louvers are open or partially open. Hence, the set points for the hardware need to be set to prohibit this scenario. Finally, the MV/TV and louver hardware have pre-set deadbands of 20 ˚C and although a change can be requested, it is in the interest of the project not to modify the hardware if possible.

Figure 9 shows the simplified heat flow diagrams of the Inner Cruise 0.65 AU Hot Case and Outer Cruise 5.6 AU Cold Case. These cases were run with an initial simplified assumption on the valves and louvers: they were assumed fully open for the hot case, and fully closed for the cold case. The RHB set points are determined by the minimum fluid temperature of the propulsion module inlet required for the WCC. Because the RHB is controlled via PRTs, a 5 ˚C dead-band was defined to accommodate the temperature sensing accuracy of the spacecraft avionics subsystem. Note, to ensure the louver is fully open during the WCH and fully closed in the WCC, the louver set points and its 20 ˚C deadband must fit within the predicted average radiator temperatures of the two bounding worst cases. Similarly, the valve set points are determined by the two bounding cases: 8 ˚C in the Inner Cruise hot case and 4 ˚C in the inner cruise cold case. These set points however, are not compatible with the capability of the MV hardware.

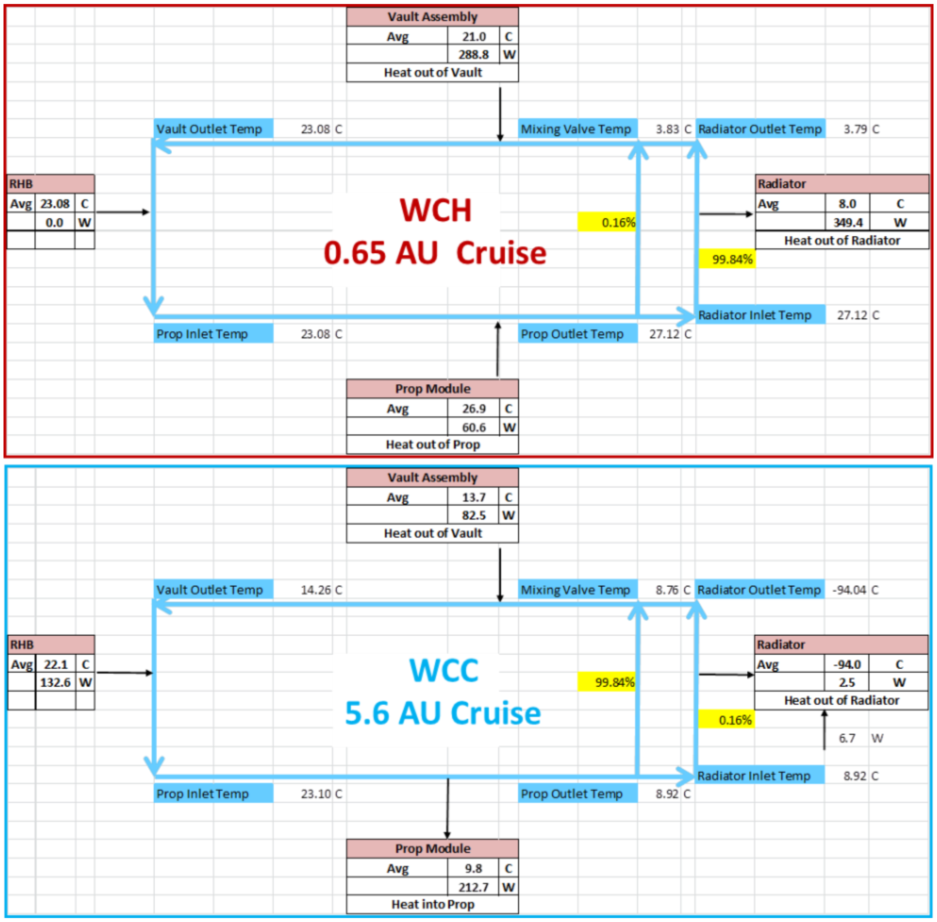

Figure 9: Simplified heat map of the HRS system of the two bounding thermal cases for 0.75 lpm fluid flow rate. Note the mixing valve and radiator/louvers are assumed fully open (WCH) and fully closed (WCC).

There are a few options to address incompatibility of previously flown MV deadbands and the needed deadband for the Europa HRS. One is to remove the TV and louvers to allow a larger percentage of fluid flow through the radiator. This would allow the fluid to drop enough in temperature such that the fluid at the mixing valve will be at a colder temperature during the WCC. However, the 15 ˚C of additional fluid temperature drop necessary for a 20 ˚C deadband requires an additional 75W of heat loss through the radiator; a significant power impact for the thermal subsystem and flight system. Alternatively, the valve design could be modified. Instead of an oil-actuated valve, a wax-actuated valve similar to what was used in Mars Pathfinder could be employed. However, this type of valve with a much tighter dead-band presents problems and uncertainties with the control authority of the fluid loop (Ref. 6). The mechanical design of the valve can also be modified, such that the inlets of the valves are spaced closer so that a 5 ˚C dead-band could span the fully open and fully closed positions. This modification carries risk due to the manufacturing tolerances of the inlets and the spacing between the ports, as well as the risk on control authority as with the Pathfinder valves. The recommended corrective action is in the next section.

E. HRS at a Higher Flow Rate

The pump could also aid with addressing the MV/TV set point concern. Because the fluid temperature delta across the spacecraft is determined in part by the fluid flow rate, a faster fluid flow can further separate the WCC and WCH MV temperatures. Figure 10 shows the temperature deltas for a system with 1.5 lpm fluid flow. Note that these results were obtained by assuming a 20 ˚C valve deadband of 4 ˚C-24 ˚C. With such an assumption, the MV/TV does not reach the fully open case in the WCH. This implies that the radiator surface area could be decreased by approximate 10% of the current 1.29m2 of radiating surface area – this is of interest to the mechanical design team as it makes the radiator easier to accommodate. The higher fluid flow rate can also decrease the temperature gradients across the spacecraft hardware, which can allow the spacecraft to operate at a lower average temperature and thereby reducing the thermal power needed at Jupiter. The savings in reducing the average spacecraft temperature are seen when comparing the WCC heat loss from the HRS system in Figure 9 and 10: 215W vs. 207W, a modest amount but still beneficial to the flight system.

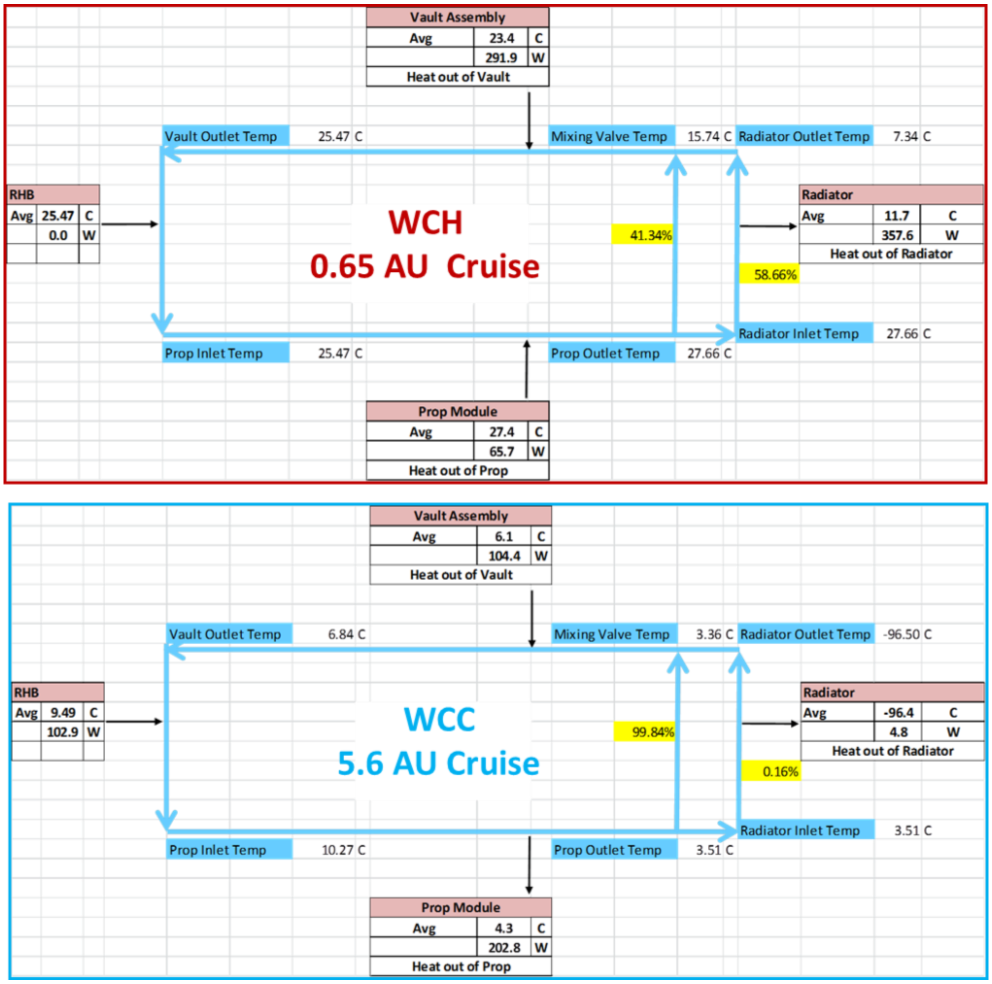

Figure 10: Simplified heat map of the HRS system of the two bounding thermal cases for 1.5 lpm fluid flow rate.

Three different options can increase the fluid flow rate: two pumps in series, increased pump RPM, or modifying the pump impeller dimensions. In all cases, the IPA power demand will increase by approximate 12W. The two pumps in series can have a significant impact on pump impedance and the IPA volume. Alternately, increasing the pump RPM could have implication on pump lifetime and heritage range of operations need to be reevaluated (Ref. 7). As of this writing, the impeller dimension change appears to be the simplest change since the impeller dimensions necessary for the pump to provide the 1.5 lpm flow has been done before by the pump vendor. Additionally, the impeller dimension change does not seem to threaten the IPA volume in growth. For all options however, a higher flow rate will significantly affect the system pressure drop. Hence pursuing such architecture will require a re-evaluation on the tubing line length and an investigation on parallel flow for portions of the spacecraft – specifically at the propulsion module as it has the highest percentage of total line length.

IV. Conclusion

The Europa Clipper HRS is based on previous flight projects and hardware heritage. However, due to the uniqueness of the mission and the spacecraft architecture, certain modifications to the fluid loop architecture and design are being incorporated and considered. The extreme radiative environment at Jupiter necessitated studies on potential impacts to the materials and fluids used in the HRS. The need to reduce power demand and heat leaks has incentivized the use of two MV in series and louvers on the HRS radiator. The expected fluid system impedance due to significant size of the spacecraft and required length of tubing passes motivated design changes on the tubing and tubing interfaces. Finally the tight temperature requirements and fight system power scarcity is requiring a change in the pump hardware to allow for a higher fluid flow rate and possibly even split flow. As the Europa Clipper spacecraft designs mature, the HRS will evolve along with it.

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